High visibility Hong-Ou-Mandel interference between independent single photon sources obtained from multi-stage nonlinear interferometers

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Abstract: Using spontaneous four-wave mixing in a 3-stage nonlinear interferometer for temporal mode shaping, we efficiently generate heralded single photons in single-mode, evidenced by a visibility of 90% in Hong–Ou–Mandel interference between independent sources.
OCIS codes: 270.0270, 190.0190

Quantum interference between independent photon sources has played an important role in quantum information processing such as quantum repeaters and teleportation. In particular, Hong–Ou–Mandel (HOM) quantum interference [1] constitutes key evidence of the purity and indistinguishability of independent single-photon sources. Such indistinguishable independent single photons must have identical spatial, polarization, spectral, and temporal modes at a beam splitter (BS) of HOM interferometer. Photons in single spatial mode can be achieved by using the single-mode waveguide, and polarization can be well matched by a polarization controller. However, matching the temporal mode is very challenging. Exquisite efforts have been put into improving the modal purity of the heralded single-photon states by specially engineering the nonlinear media with just the required dispersion to achieve single temporal mode operation [2]. However, because the nonlinear interaction and linear dispersion are often mixed in parametric processes, limited successes have been achieved so far only at some specific wavelengths with sophisticated design. We recently propose to achieve precise state engineering for near ideal single-mode operation and near unity efficiency by using a multi-stage nonlinear interferometer (NLI) [3]. This new method, which separates the spectral control from nonlinear interaction, can be used to obtain heralded single photon sources (HSPS) simultaneously possessing the properties of high purity, high collection efficiency, high brightness, and flexible tunability. In this paper, we experimentally demonstrate the high indistinguishability of the heralded single-photon sources so produced with a HOM interferometer. In the NLI, the dispersion-shifted fibers (DSF) and standard single-mode fibers (SMF) respectively functions as the nonlinear gain media and controllable spectral phase shift to achieve a factorized joint spectral function (JSF) of photon pairs. In the HOM interference between two independent heralded single-photon sources generated by the three-stage NLIs, the raw data shows a visibility of 81%±6%. After correcting the Raman scattering effect, the visibility of HOM interference is about 90%±6%.

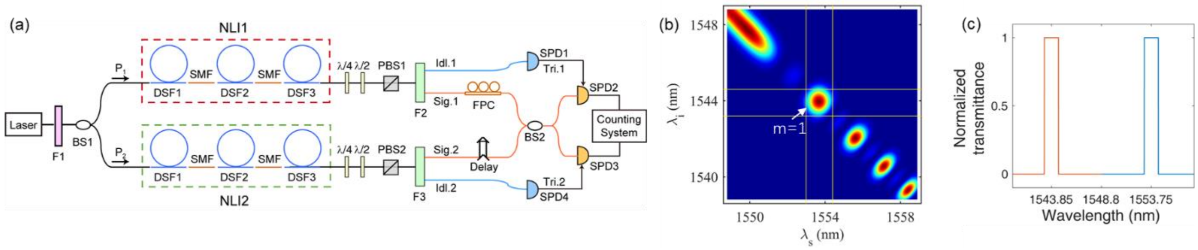

Fig. 1: (a) Experimental scheme for observing HOM interference between two independent sources of heralded single photons generated by NLI. (b) Contour plot of joint spectrum intensity function out of each NLI, formed by three pieces of DSF with SMF placed in between two adjacent DSFs. (c) Spectrum of DBF. P1-P2, pulsed pump; NLI, nonlinear interferometer; DSFs, dispersion shifted fiber; SMF, single mode fiber; F, filter; DBF, dual-band filter; FPC, fiber polarization controller; BS, 50/50 beam splitter; SPD, single photon detector.

The experimental setup is shown in Fig. 1(a). Each heralded single photon source is realized by a three-stage NLI consisting of three identical 150-m-long DSFs and two 20.8-m-long SMF. The liquid nitrogen cooled DSFs with zero dispersion wavelength of 1548.5 nm are the gain media of spontaneous four wave mixing (SFWM), while the SMFs are used to precisely control the spectral phase shift. When each NLI is pumped by pulsed laser with pulse duration, 3 dB bandwidth and central wavelength of ~ 4.6 ps, 1 nm and 1548.8nm, respectively, the JSF out of each NLI is shown in Fig. 1(b). Clearly, the JSF follows a quasi-periodically varying interference profile and exhibits some kind

This is the author's manuscript of the article published in final edited form as:

Li, J., Jie, S., Cui, L., Li, X., & Ou, Z. Y. (2019). High visibility Hong-Ou-Mandel interference between independent single photon sources obtained from multistage nonlinear interferometers. 2019 Conference on Lasers and Electro-Optics (CLEO), 1–2. https://doi.org/10.1364/CLEO_QELS.2019.FTh3D.5

of “islands” pattern. A rectangularly shaped dual-band filter (see Fig. 1(c) for its spectrum) centering at 1543.85 and 1553.75 nm is used to isolate the photon pairs corresponding to the most round shaped island (labelled as m=1 in Fig. 1(b)). Because the NLI functions as an active filter of the photon pairs via SFWM, the DBF with bandwidth of 1.4 nm extracts out the frequency uncorrelated photon pairs without introducing extra noise photons. Because the correlated photon pairs from SFWM are co-polarized with the pump while the noise photons from spontaneous Raman scattering (SRS) are scattered to all polarization directions, we employ quarter wave plate, half wave plate and PBS at the output port of the NLI to further suppress SRS. The detection events the of single photon detector (SPD1 or SPD4) placed in idler channel herald the existence of a pure state single photon in signal channel. In the experiment, we first check indirectly the mode purity of the generated photons by measuring the second-order intensity correlation function $g^{(2)}$ of the field in individual signal channel. The result is $g^{(2)}$~1.8 (1.95) without (with) correcting the Raman noise, close to the single-mode value of 2 [4]. And the collection efficiencies, defined as the ratio between coincidence of photon pairs and individual counts in signal/idler channel, for both signal and idler photons (excluding detection efficiency) are ~94%.

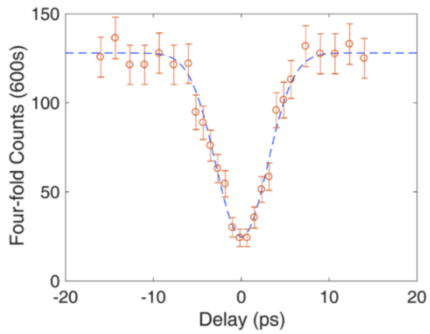

Fig. 2: The raw data (with only dark counts of each SPD subtracted) of four-fold coincidences as a function of the relative delay between the two HSPS. The dashed line is the fitting of Gaussian function.

To directly verify the high mode purity of HSPS, we perform HOM interference measurement between two independent HSPS. In the experiment, the pumps (P1 and P2) of two NLIs need to be synchronized. We achieve this by dividing the output of a mode locked fiber laser into two with a 50/50 beam splitter (BS1). Before combining the two HSPS at 50/50 BS2, the signal field out of DBF2 is delayed by a reflector mirrors mounted on a translation stage. To ensure the matching of polarization mode, polarization of signal field out of DBF1 is properly adjusted by FPC. The overall detection efficiencies for the signal and idler photons (including insertion loss of DBF1 or DBF1) is ~5%. Fig. 2 shows the four-fold coincidence counts of the four SPDs (SPD1-SPD4) as a function of delay. The blue dashed curve is the fitting of the Gaussian function. During the measurement, the pump power is 55 μW (0.04 photon pairs per pulse), the measured visibility of the HOM interference curve is 81%±6%. However, in our experiment, there are not only correlated photon pairs generated by SFWM in fibers, but also the photons generated by SRS as the background noise. After characterizing the portion of SRS and correcting the Raman scattering effect, we find the visibility is 90%±6%.

In conclusion, our experimental investigation verifies that the multi-stage NLI provides a new approach for engineering the spectral property of photon pairs and for obtaining photon pairs simultaneously possessing the advantages of high purity, high collection efficiency and high brightness.

The work is supported in part by the National Natural Science Foundation of China (11527808, 91736105, 11874279).

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